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Challenges in Teaching Architectural Morphogenesis

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Abstract: *Reviewing the successive cognitive, operative and constructive models of architectural morphogenesis through time, the paper first recalls students and teachers in architecture how designers started experimenting digital design to reach self-generative, morphogenetic morphologies. Generally referred to as "non-standard architecture", this innovative morphogenesis favours a new kind of spatial and architectural audacity but also generates three types of rupture: i) a rupture between form and structure; ii) a rupture in terms of process continuity and iii) a rupture in terms of multi-disciplinary collaboration. We consequently have to acknowledge the fact that, at a current state, non-standard architecture still struggles in terms of self-coherency and implementation, leaving a large amount of projects at their virtual, embryonic state especially in pedagogical contexts. We believe the challenge resides in overcoming the overly simplistic and reductionist appeal of purely formal and visual non-standard architecture: these morphologies should, on the contrary, be intrinsically defined by their form and structure relationship. We suggest such reconciliation should occur during the early stages of architectural education. Two experimental instruments, that perhaps constitute interesting renewed pedagogical models, are reported in this paper and we conclude by listing the remaining challenges when it comes to the teaching of architectural morphogenesis.*

Keywords*: architectural morphogenesis, non-standard architecture, teaching processes.*

Architectural Morphogenesis through Time: A Review of Design Models

Historically, nature and natural phenomenon have inspired builders, more or less consciously, in their way to construct and inhabit spaces. Until, and including, the well-known architectural style "Art Nouveau", this inspiration essentially confined to mimic aesthetic proportions and lines as a way to renew decorative trends. Architectonic intentions would nevertheless progressively emerge, through the work of architects as Antonio Gaudi for instance. Researching what Leonardo da Vinci had completed three hundred years earlier, Gaudi started observing his natural environment and moved toward some form of "total art", unifying shape, space and function in a global, coherent architectural proposition where different parts were more than the simple addition of autonomous elements.

Beside the attempts of Gaudi or Wright, who will later be called the "pioneers of Organic Architecture", we have to mention the work of Louis Henri Sullivan and Rudolf Steiner. Expanding their research beyond stylistic coherency, those two renowned architects looked at nature as a way to inspire new creative processes (Theissen, 2011). Demonstrating the intrinsic relationship between form and function, Sullivan is the first one to conceptualize a generative process capable of creating "natural shapes" in architectural design. From there, the quest of Organic Architecture won't limit anymore to stylistic research but will thrive towards holistic design strategies, getting inspiration from both natural shapes and natural processes.

Reviewing successive models of knowledge, be they cognitive, operative or constructive, the following section aims at offering both students and teachers in architecture a more holistic overview of architects' attempts, through time, to understand, develop and master architectural morphogenesis, seen as "the process through which an object or being *[here the architectural artefact]* comes into existence and develops its form" (Farzaneh, 2012, p. 585). An overview that could, in turn, later inform radically innovative and renewed teaching models.

Biological Inspiration and Biomimicry

In the 70s and 80s, so-called "bio-inspired" or "bionic" models spread out as a new source of inspiration for architectural design, taking roots in structural concepts and theories developed during the 50s. At that time, architects like the German architect Frei Otto or the Mexican Félix Candela had started experimenting pioneering tensile structures or thin shells made of reinforced concrete, and built emblematic structures such as the Munich Olympic Stadium. Architects and structural engineers started to extract building and structure concepts from natural and biological principles and applied them to architectural productions.

These attempts initiated biomimicry, defined by Janine Benyus as "the art of drawing inspiration from natural shapes, processes and ecosystems, in order to innovate in a sustainable way" (Benyus, 2011). Becoming, since then, an important source of inspiration for designers, biomimicry intrinsically seeks to maintain – or restore – the balance of nature that tends to disappear as soon as human beings step in. Sometimes qualified as "behavioural", biomimicry transcends natural shapes while always trying to understand underlying principles of those shapes and systems (Pawlyn, 2011).

First Generative Processes in Architectural Morphology

D'Arcy Thompson, intellectual born in 1860, is said to be the founding father of most of the research done on structural morphology. This field is defined as the study of form in relation to the pathways of forces transiting in the structural elements materializing the shape (Bagnéris, 2009). Thompson built his ground theory exclusively by observing forms/forces relationships and established that shapes are simply the consequence of physics deformations. Some architects still currently apply this approach and try to design "rational shapes" uniquely defined by natural laws and forces, such as surface tension or gravity force. The elements, as a consequence, dilate and distort on basis of a pre-defined model and become, per se, simple mathematical resultants that can be studied and visualized using geometrical analysis tools. Jean-Marie Delarue, in Frei Otto's "IL 27" (freely translated, 1981), comments:

> We already knew, at least in light of D'Arcy Thompson famous book *"On Growth and Form"*, that the deep understanding of shapes required the deep understanding of generative processes.

D'Arcy Thompson, throughout his research, foresaw how his theories could apply to infrastructures and engineering structures such as buildings or bridges. Studying efficiency of specific morphologies, he demonstrated for instance the structural analogy between vultures' metacarpus bones and Warren's beam profiles, or similarities between tensile strengths inside humans' femoral heads and cranes. He always studied structural designs' fundamental principles, performances or material optimization in light of similitudes with physics, natural or biological phenomenon. In this regard he commented (Songel, 2010):

> The search for differences or fundamental contrasts between the phenomena of organic and inorganic, of animate and inanimate things, has occupied many men's minds, while the search for community of principles or essential similitudes has been pursued by few.

A few years later, Robert Le Ricolais expanded those principles beyond structural implementation and rather considered them as intrinsic architecture *raison d'être*, relating some powerful poetic meaning on top of rational considerations. Not an architect, nor an engineer or mathematician, this experimenter explored light, modular and industrialized structures mainly on basis of intuitive, experimental, essay-and-error manipulations. He was interested in the development process rather than in the final solution, supplanting traditional "fullness and emptiness" architectural concepts by more innovative notions of "continuity and rupture" (Schimmerling, 1994). Researching space partition laws and forms/forces relationship, he is said to be the first one to officially theorize **morphology as a science of architectural design**.

The study of natural forms / forces relationships and the renewed models of knowledge and design process they offer (on both a cognitive and operative level) have later been considered as inspirational by many architects. Gaudi declared, about referring to the shape of bones to design his Casa Batllo, that "originally it was just like a return to the origins" (Mimram, 1983). Frei Otto would later discuss biomimicry and argue that the most adequate attitude would be to refer to animated living things rather than simply mimic their shapes. This, from his point of view, enables architects to require buildings to be lighter, more energy efficient, more natural, adaptable and mobile. He pursued this quest through pioneering structures such as tents, canopies and inflatable membranes. Remarkably, avant-gardist propositions like those were essentially developed in regard of scientific and technological improvements. Little by little, experimentation and application of innovative technologies supplanted studies of natural laws and phenomenon in the development of generative processes for architectural morphogenesis: from cognitive and operative, the renewed models of thought slowly evolved towards constructive, experimental models.

Other Techniques, other Zeitgeist: towards Fragmented and Heterogeneous Morphologies

Cubist, surrealist and other architectural movements all sought to renew, or even suppress, traditional codes of architectural aestheticism and formalism, deeply resonating with 19^{th} and 20^{th} centuries' constant technological progresses, in light of other disciplines Zeitgeist. At first, those new architectural investigations mainly remained an attempt to create original spatiality, whereas very fewer experiments really inquired new mathematical knowledge (as it was the case for Gaudi, when he tried to overcome semicircular and pointed arches in his Sagrada Cathedral). Yet, this societal desire to detach from more traditional styles and representation modes let the artists and architects discover innovative techniques as well as unexpected materials offering new mechanical characteristics. Elastic, viscous and soft materials would largely expand their research towards deformation, movement, instability, rupture and randomness. Technical advances, simultaneously, with their production and fabrication possibilities, offered designers renewed ways to express their perception of real (and unreal) worlds.

These last 20 years, digital developments enabled new medium for expression and representation and even enlarged the possibilities to experiment. In architectural design, software was first used to ease calculations and transfer information. But architects such as Gehry or Eisenman quickly understood the potentialities of digital design and tested them in several projects, developing deconstructivist approaches that would slowly erode traditional codes of architectural language (Silvestri, 2009). Architectural shapes became the expression of **conflicting logics, experimentations of fragmentation and heterogeneity**. Lacking dedicated tools for architecture, those designers resolved to deviate the use of digital interfaces initially developed for automotive design or aeronautics, for instance. Doing so, they reached innovative shapes that were, until then, hardly describable or representable through traditional codes of Euclidian geometry (Silvestri, Fleury and Bagnéris, 2012).

Self-generative and Morphogenetic Processes: from new Creative Models to new Architectonic Artefacts

History reminds us that Gaudi, pioneer in several areas of architectural design, also was one of the first to voluntarily renounce to (some of) his role of creator to rather adapt his concepts to the reactions and behaviours of the scale models he built early and through ideation. Those prototypes, essential to his experimental design process, were indeed submitted to external forces that would define shapes' boundary conditions and participate to **self-generative processes** of shaping architectural artefacts. Starting from a rather traditional typological scheme, Gaudi this way reached highly innovative solutions, both complex and convincing in terms of spatial and architectural coherency (Tomlow, 1989). Such experimental process insures achievement of a structurally stable shape; though, at Gaudi's times, it disadvantageously required the abandonment of traditional models of Euclidian geometry. The architect thus had no available descriptive language, method nor tool to codify representation, nor to transfer information to the construction site. This handicap would last several decades, as Heinz Isler (in the 50s) would still use funicular experimental models to design his concrete shells (Isler, 1959; Ramm and Schunck, 1989).

Figure 1 Funicular model of Colonia Güell, Antonio Gaudi, 1898-1916.

Those early attempts, and the shapes they generated, were consequently not anymore the result of a single individual and subjective will (or attempt), but rather the result of self-generative, self-shaping processes. Those shapes reached some form of structural clarity (some might say purity), but couldn't be properly described by any of the available tools or methods, given the complexity biding intrinsic forms and forces relationships. Gaudi and his contemporaries paradoxically had already reached a first technological bottleneck, one that would later be experienced again by the first experimenters of digitally designed conflicted and fragmented shapes.

Facing this paradox, Greg Lynn has been one of the first to consider digital design not only as a way to design fancy, deconstructed innovative forms, but rather as a contemporary experimental setting able to reach a new kind of constructive model based on self-generated and thus stable shapes, this way pursuing a new kind of **morphogenetic design process**. In his quest to restore intrinsic unity in a world where digitally designed architecture rather looked like an addition of exploded elements, he developed several concepts such as "fold" or "blob[1]" (Lynn, 1993).

Lynn used the term "fold" to theoretically formalize and describe architecture as a dynamic organization system rather than a formal design process or functional

[1] Blob – or Binary Large Object – is a term borrowed to the software engineering world rather for its popular definition, referring to a shapeless, awkward object, notably used in 1958 Irvin S. Yeaworth's movie.

organization. Likewise the term “blob” is used to describe soft architectures and shapes whose main characteristic is to present points that can be freely displaced in any other spatial spot (Figure 2). The software used enables intuitive transformation of any point belonging to this blob shape, and computes new positions of any neighbour point, adapting to the laws and forces ruling the active surroundings. Those virtual blobs, digitally created, emerge and behave given the contextual constrains defined by the designer and challenge the verticality embedded in architectural traditions. The architect’s control over the shape isn’t still totally complete, though, as connected points also self-reorganize in regard of the active context, given various constraints they have to apply to.

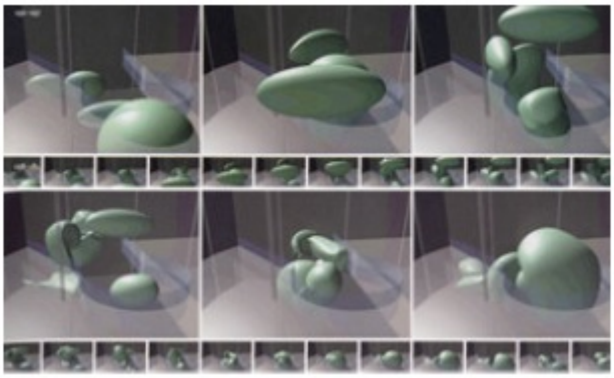

Figure 2 Blob Architecture: the form is generated by the dynamic organization of the contextual force. Greg Lynn and Henie Onstad, Oslo, 1995, in Silvestri, 2009.

Although blobs generate a new kind of language consistency from early phases of ideation until conceptualization of technical details, they still face large implementation issues in regard of their transcription into the real, constructed world, such as exceeding time and cost previsions, or singularity of structural components. “Gridshells” constituted a first available solution to overcome those issues: very few of them have been built, but one of the first was designed by Frei Otto in Mannheim (Wendland, 2000). This structure takes the shape and rigidity of a double-curve shell, and is the result of a planar grid submitted to deformations (Figure 3). Otto would build such a grid using simple bars connected in two directions, whereas Ban and de Gastines (in the late Pompidou centre) would rather use larger, articulated beams able to bear larger deformations.

Figure 3 Multihalle, Frei Otto, Mannheim, Germany, 1975.

As a matter of a fact, and independently of the architectural era, the more the building would be complex, the more the technical realization would require multiplication of assembly points, and thus the more the structure would cost. Moreover, those construction techniques, although they enabled the building to fit the designed curve, still did not insure the material coherence and continuity intended by the architect. Last but not least, given the growing complexity of the required modelling tools, architects would slowly loose control of parts of the design and formal process. Greg Lynn, acknowledging this new paradox, admitted that “sometimes the computer takes control: its formal language guides you in your process” (Lynn, 2004).

The Emerging Paradox of Non-standard Architecture: the Rupture between Form and Structure

Reviewing the successive cognitive, operative, constructive models of architectural morphogenesis through time, we distinguish here three main phases that would deeply shape their development.

First, descriptive and representational tools developed during Renaissance enabled architects to experiment geometrically constrained (or analytical) shapes, defined by a set of rules from Euclidian geometry.

Later some experimenters, as presented above, reached new kind of “mechanically constrained” shapes, generated this time by experimental essay-and-error trials mainly conducted on reduced scale-models. Those shapes, defined by intrinsic forms and forces relationships, would translate static equilibriums. Although following a set of rather constraining natural laws and forces, they would considerably enlarge architects’ space exploration. At first quite challenging to describe geometrically, emerging digital computing would considerably ease their transmission to the real world.

These last decades eventually saw new families of shapes and design processes emerge, far away from more traditional static or orthogonal solutions. Architects indeed started to experiment digital design, first as a way to generate fragmented, conflicting shapes, later as a way to renew the design process itself, reaching self-generative, morphogenetic morphologies. *Blob, flexible shapes, free-form, liquid, digital shapes* are as many ways to describe these new families of shapes, stimulated by the recent progress of software engineering and modelling. This innovative morphological category, generally referred to as **non-standard architecture**, consequently describes projects that do not fit into generally admitted design processes and rules (Picon, 2010). Digital tools, with their over-simplified interfaces, enable architects to elaborate shapes that are not describable through traditional Euclidian geometry anymore, but rather proceed from complex mathematical models (Bezier curves, splines, nurbs, …) that favour a new kind of **spatial and architectural design audacity**.

Although they indeed constitute new ways to leverage architectural innovations, these processes and digital design products nevertheless involve other levels of complexity, specifically in terms of communicating and transferring the conceptual project to the real, constructed world (Bagnéris, 2009). Hardly communicable to engineers and contractors, these new morphologies indeed generate several complications in terms of implementation and building processes. This level of complexity causes **ruptures in terms of collaborative processes**, misunderstandings and synergy problems between disciplines that hardly share the same models of knowledge anymore. The Pompidou Centre in Metz is one example of such complexities, but we might as well mention here the Frank Gehry Guggenheim Museum, the Yokohama Terminal from FOA architects or, among others, Massimiliano Fuksas' trade fair in Milan (Bagnéris, 2009). The issues met on those building sites are multiple: highly complex and costly study of the structure; difficulty to find contractors willing to produce often unique components of such frames; technical impossibility to respect the initial fluid formal intent, reaching a paradoxically fragmented end-product and creating a rupture in terms of intent and **process continuity**. Most of these prototypes, although highly promising in terms of morphogenesis evolution, rather end up jeopardizing their own credibility because of building processes suffering of literally exploding costs and prescribed timings, without even mentioning the later maintenance issues and premature aging those structures generally face. We have consequently to acknowledge the fact that, at a current state, non-standard architecture still struggles in terms of self-coherency and implementation and is facing a challenging **rupture between form and structure,** leaving a large amount of projects at their virtual, embryonic state. We believe the challenge resides in overcoming the overly simplistic and reductionist appeal of purely formal and visual non-standard architecture. Non-standard architecture should, on the contrary, be intrinsically defined by its implementation process and should reconcile what essentially defines it, which is the form and structure relationship. Some prototypes are being developed (see Bagnéris' work below, or Mutsuro Sasaki's work on structure flow concept) and are for instance particularly interested in the implementation of algorithms able to render more interactive exchange with architects . They gradually make their complex geometries evolve, either towards some kind of forms hybridization, or towards the definition of generating rules for complex geometry definition (Bagnéris, 2009).

We suggest that such reconciliation should occur during the **early stages of architectural education**: let's help students better understand the richness and diversity of non-standard morphologies, while teaching them renewed ways to process them. Let's consider again architectural, engineering and technical processes side by side and let's guide students towards a coherent continuum of concepts and information, early on from the first steps of ideation until the later phases of implementation. Next section will shortly review various pedagogical approaches that have been recently implemented in architecture curricula, and more specifically focus on two research settings that could, we believe, provide interesting new paths for teaching architectural morphogenesis.

Experimental Instruments to teach Architectural Morphogenesis

Non-standard architecture, and more globally speaking architectural morphogenesis, is consequently facing today a double challenge: either formal aspects are not related anymore to the other sides of the project, which leaves room for incoherency, or the current engineering tools have reached another bottleneck in creating (and supporting implementation) of new families of shapes.

Facing these challenges, some pedagogical settings have been recently implemented to test new ways to educate young architects to the underlying challenges of designing non-standard architectural morphologies. A first stand is to approach the question of architectural morphogenesis through the lens of geometry education. Pottman and his colleagues, for instance, are developing the concept of “architectural geometry”, i.e. a new branch of mathematics specifically designed for architecture and supporting the development of architectural free-form structures (Pottman, Schiftner and Wallner, 2008). Building on those mathematical models, the authors develop several algorithms to digitally enhance the design of ruled surface panels. Those panels, authors conclude, constitute an efficient way-through covering complex geometrical shapes, but “structural aspects have to be incorporated as well” (p. 27). One could also mention attempts in teaching architectural morphogenesis using performance-driven models, or through programming and scripting classes seen as a way for young architects to surpass and master current codes’ limitations, even extending the capabilities of those codes through scripting self-made plug-ins (Grobman, Yezioro and Capeluto, 2009).

Another approach, as developed for instance by Reissig and Castro-Arenas, suggests formal and visual-based learning as a way to explore issues related to complex form and structure relationships. These authors designed a didactic “design puzzle” including pieces of various sizes and morphologies that help students reach systematic juxtaposition (or dissection) schemes of form generation. This puzzle equips the exploration of complex morphological themes through visual and manual manipulation of minimal parts and enable more efficient appraisal of 2D and 3D variables and parameters (Reissig and Castro-Arenas, 2013).

Two other attempts more specifically draw our attention in the context of this paper, and will be further discussed in the following sections: *pForms* and *material-based design.* They indeed rely on the two main pillars of architectural education and knowledge, respectively iconic (visual, diagrammatic) and enactive (concrete, experiential) modes of thought (Kolb, 1981, in Hanson, 2001), representative of the well-known analogy of architectural design seen as a process of “reflection in action” (Schön, 1989). Those two experimental instruments, we believe, might indeed very well become new pedagogical models for teaching architectural morphogenesis, and therefore ease reconciliation between form and structure inside contemporary morphologies.

pForms as new Pedagogical Process assisting Representation and Design of Non-standard Architectural Morphologies

Marine Bagnéris' thesis, titled "*Contribution to design and implementation of non-standard morphologies: the pascalian forms*" (freely translated, 2009), suggests further developments of Marty's pascalian forms (or pForms, 2004), developing them as a whole new process to assist designers in generating and describing non-standard shapes. Bagnéris argues this process is able to limit the rupture between form and structure, between the design phases and between the various stakeholders involved in a non-standard architectural project.

The pForm process (Figure 4) progressively help students to build, in a synthetic, and coherent way, both the shapes belonging to Euclidian geometry (segment, face, cube, cylinder, torus, …) and the more recent ones generated through modelling software (Bezier curves, splines, nurbs, coons, …). It tackles two possible design scenarios: either the morphology is first defined, and there is need for a structure that could coherently fit this shape; or the morphology is still evolving and remains an open form-finding process. pForms this way assist less advanced designers in their understanding of the design tools beyond simple visual formalism, which eases the continuity between early concepts and implementation into coherent digital models. pForms are also developed around simple vocabulary, easily accessible to various stakeholders, which helps understanding the project morphology as well as communicating around the various problems encountered when implementing it on site.

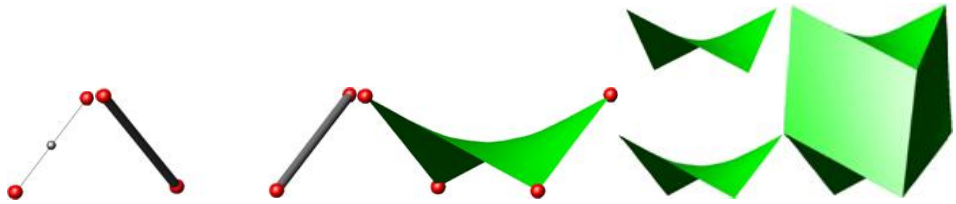

Figure 4 Example of shape generated through one pForm process

On basis of this pForm process, Bagnéris designed pedagogical experimentations with students (from ENSA Montpellier, France) in order to evaluate how they would react both to pForms themselves, and to a new kind of design process that doesn't focus exclusively anymore on visual and formal developments. Experiments were conducted with three distinct, market-ready software (SketchUp, Autocad and Blender) and through two distinct protocols.

The first protocol would simply require the students to "play around" with the software. They would freely generate non-standard shapes, without really understanding their mathematical complexity nor being concerned with any technical requirements. A second step would then to ask the students to re-sketch the shapes they just digitally designed, i.e. trying to fit their original curves while being asked to specifically analyze their geometrical and technological aspects through the lens of the pForm thinking process. Matching hand drawn shapes with the pForms process helped them understand the intrinsic software framework, and consequently to further control its impactful parameters.

The second protocol would require the students to use the software following a step-by-step methodology. For instance with Blender, students would be asked to first use the free-form deformation tool in order to create half a cylinder. Doing so, students would realize how difficult it is to control the overall deformation, especially when one doesn't understand the tools' functionalities, and more importantly their repercussions on shapes. Second step would be to use the pForms process, first by defining control points on horizontal sections. Several models would enable students to study the numerous profiles obtained by each horizontal section, and to better understand how the section would evolve depending on the height. Likewise, vertical sections would refine their understanding of the intrinsic characteristics of the plane used to match the shape. As a consequence, and thanks to several exercises, students would eventually understand how many control points and sections are required to sufficiently grasp the complexity of a non-standard shape. The third and last step would be to translate the result into Ruby code until obtaining a coherent shape in Sketchup (Bagnéris, 2009).

According to Bagnéris, pForms processes are particularly efficient for several stages of the teaching process:

- Simplification: shapes are structured on basis of elementary curves, easily identifiable and modified through successive and simple operations;
- Continuity: pForms constitute a form-finding and generative process built on elementary rules that insure coherency from early-stage design to implementation;
- Users acceptance: the pForm process insists on understanding the fundamental framework of the used software, which eases explanations and engagement;
- Compatibility: this process can basically by adapted to any kind of modelling software, which also eases users adoption since anybody can use her favourite modelling tool.

Pedagogically speaking, the pForm process assists students in mastering non-standard form-finding processes mainly through helping them better understand the underlying geometrical complexity of their work. Being in control of their digitally designed project, students are more apt to tackle complex simulations and optimization processes, and therefore more apt to better understand how forms and structures articulate, which is remarkably demonstrated through the coherent scale-models they would later build of their projects. Becoming more intelligible, complex shapes rely on a more conscious, step-by-step methodology that insures more coherence (technically and structurally speaking) to more audacious projects.

Bagnéris nevertheless underlines that the results reached through the pform process are currently limited to geometrical studies of architectural structures. Mechanical, material and technical studies should be further conducted to enhance and complete this pedagogical model.

Material-based Design as a new Inspirational Process in Form-finding, Morphological architecture

Another way to overcome the rupture between form and structure is to be found in material-based design methodologies. Starting from intrinsic material (mechanical, physical) properties, several researchers indeed recently developed innovative morphological solutions (see for instance Tibbits, 2012 or Tibbits and Cheung, 2012).

German architect Achim Menges, for instance, exploits genetic algorithms developed in the last decade to reproduce active phenomenon that shape natural materials, using them during generative form-finding processes. More specifically, Menges used these algorithms to reproduce pinecones natural hygroscopic behaviours: pinecones open and retract depending on the air moisture level. This phenomenon, due to woods' anisotropic characteristics, can be applied to architectural elements and therefore became inspirational for the architect through his 2012 "HydroSkin" project, a meteorosensitive pavilion that reacts to climatic changes. "The material exercises an influence on the geometry, and vice versa: the geometry defines the state and the behaviour of the material in such and such space-time area" (Brayer and Migayrou, 2013). Here the material behaviour and its structure generate the pavilion shape: the material intrinsic characteristics are at the basis of a new morphology, corresponding to what is referred to as **material-based design**.

Joris Laarman's furniture design "Bone Furniture" (Figure 5) also integrates this sphere of influence (Brayer and Migayrou, 2013). Going beyond some mimetic approach, this designer observes and models how bones and vegetables grow, and then expands the genetic algorithms into optimization algorithms that will be applied on architectural shapes and structures. Line codes subtract or add matter where it is really needed, similarly to mechanical engineering optimization processes, but this time getting inspiration from natural and biological structures' growth.

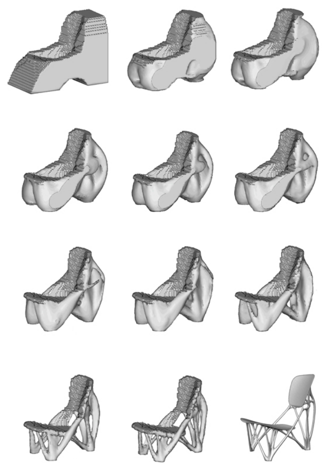

Figure 5 Optimization process of a chair from the Bone Furniture collection, Joris Laarman, 2006

Other architects innovate on basis of biological resources themselves. Recently, Neri Oxman got inspiration from larva generative processes to design her Silk Pavilion (Oxman, Laucks, Kayser, Duro-Royo and Gonzales-Uribe, 2014). On a tri-dimensional structure she placed some silk threads, on which some 6500 silkworms slowly acted as "biological printers", generating a second-level structure reinforcing some parts of the initial structure (Figure 6). Following Oxman, architects this way commit to a new kind of design intelligence, a more qualitative than quantitative approach of materiality: a "Nature 2.0" approach (Brayer and Migayrou, 2013).

Figure 6 Silk Pavilion, Neri Oxman, 2013.

Influenced by Gaudi or Otto's first empirical tests, material-based designers favour physical experimentation starting from physical or mechanical properties of natural materials, and transfer this knowledge to shapes that become intrinsically more adapted to materials' physical properties, and therefore to their implementation.

Aside from more visual-based and hands-on learning methods such as Reissig and Castro-Arenas' (see above), literature does not yet report much attempt to adapt such material-based methodologies to educational contexts and constraints. The time-consuming, iterative aspects of experimental settings might perhaps explain this current restraint. We nevertheless believe that a first, simple manipulation of next-generation material libraries and a deep assessment of those materials' respective properties might already push architectural morphogenesis further towards innovative propositions.

Remaining Challenges in Teaching Architectural Morphogenesis

This paper considered, at first, how morphology evolved through time. Defined by Goethe as "the study of forms and structures under every possible aspects (physical, abstract, perceptive or symbolic, functional or spatial, spatial or temporal)" (Schimmerling, 1993), this interdisciplinary science has been heavily explored, especially by architects of the beginning of the 20th century who were in desperate need to find alternative and renewed ways to define architectural space.

Through their constant attempt to innovate, some architects more recently tested new potentialities of digital tools (sometimes initially developed for other disciplines) and implemented first experiments of non-standard architecture. This non-standard architecture, even though offering architects new ways to leverage spatial and morphological audacity, generates three types of rupture discussed in the second part of the paper: i) a rupture between form and structure; ii) a rupture in terms of process continuity (from early design phases to implementation) and iii) a rupture for multi-disciplinary collaboration, multiple stakeholders of such complex design projects hardly sharing similar knowledge and skills anymore. In a third part, the paper explores recent attempts in teaching architectural morphogenesis, and more specifically reports on two experimental instruments (pForms and material-based design) that might help overcome those ruptures, especially if integrated soon enough in early stages of architectural education.

As a conclusion, we want to stress the need for new pedagogical models to teach architectural morphogenesis that will help new-generation architects overcome the current paradoxes of architectural morphology. We suggest that models focused on **structural morphology**, defined as "the study of shape in regard of how forces transit inside the structural elements defining this shape" (Bagnéris, 2009), might be an interesting research path, along with other crucial dimensions of the design project such as function for instance. This approach, whose main goal is to support the design decision-making process, relies on several disciplines and is entitled to study architectural morphologies and morphogenesis through several complementary viewpoints: forces, materials, environmental considerations such as energy consumption or life-cycle, implementation and fabrication processes, function, cost, and perception. Coherent communication and sharing of data between stakeholders about these intertwined and complex considerations is therefore key to the process. This theoretical (and collaborative) model moreover must be supported by augmented morphological tools that should be genuinely adapted and designed in regard of architects' needs, perhaps consequently moving away from currently deviated, i.e. maladapted, software solutions.

Those morphological tools will have to integrate additional considerations such as material mechanical properties (e.g. rigidity or resistance), easily introduced and manipulated through the design project. Such digital tool would additionally equip structural optimization, nowadays out of reach from traditional Euclidian geometry or simple physical experimentation. Aesthetic, formal and structural aspects of the project would this way reach some reconciliation and the architect, while recovering a better control of the whole design process, might moreover reach some kind of morphological and creative symbiosis.

In this regard, we should at last underline that being an architect won't probably limit anymore to designing shapes, void and materiality in regard of some specific use, but rather expand towards designing **architectural logics, form-finding and -shaping generative processes**. As Bagnéris suggests (freely translated, 2009):

> Shape becomes a process, born thanks to organic and mechanical rules, and algorithms consequently become the description of a process, being it natural or artificial.

This doesn't mean architects will have to give up their creative capacities per se, but rather that they will have to learn how to put their capacities, such as conductors, to work to the benefit of generative processes, defining audacious morphologies whose guide-lines only they will be in control of.

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Figures Webography

Fig 1: www.gaudidesigner.com, visited on Feb., 15th, 2015

Fig 2: Silvestri, C. (2009). *Perception et conception en architecture non-standard.* PhD Thesis, University of Montpellier 2.

Fig 3: www.panoramio.com, visited on Feb., 15th, 2015

Fig 4: www.lmgc.univ-montp2.fr/CS/Morpho.htm, visited on Feb., 15th, 2015

Fig 5: http://hellomaterialsblog.ddc.dk, visited on Feb., 15th, 2015

Fig 6: http://hellomaterialsblog.ddc.dk, visited on Feb., 15th, 2015